UNIK4230: Mobile Communications – Spring 2015

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Combating the Effect of Fading in Mobile Systems (Chapter 5)

26 February 2015

Agenda

- Introduction of fading
  - Effect of fading
- Diversity and types of diversity
- Combining techniques of diversity
- Equalizers
- Exploiting multipath with MIMO

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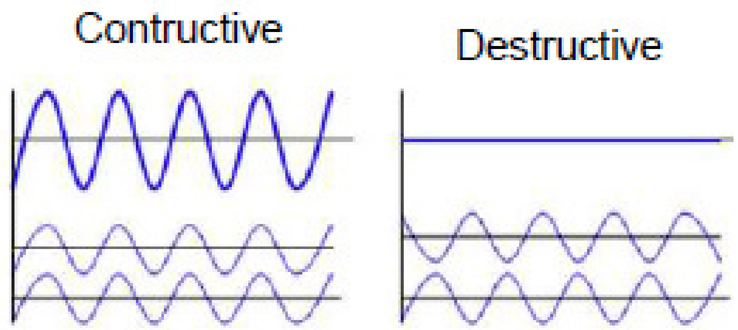
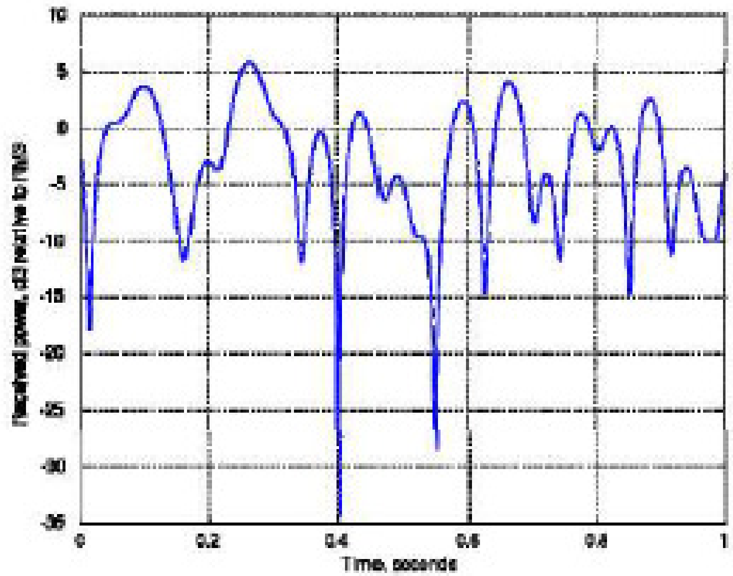
Introduction

- **Fading leads to-**
  - Quick signal variation (Rayleigh, short term)
  - Slow signal variation (lognormal, long term)
  - Inter-Symbol Interference (ISI)

- **Varying ways to combat fading-**
  - Micro diversity
  - Macro diversity
  - Channel equalizer





Effects of fading (I)

- When signal varies, Signal-to-Noise Ratio (SNR) varies and Bit Error Rate (BER) varies over time.
  - The total BER becomes larger than in a non-fading case with the same average power
- For BPSK modulation (details in *Lec 6 - Modulation*), probability of error with and without fading becomes:

$$p(e) = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\gamma_0}\right) \quad , \quad \text{without fading}$$

$$p_{fad}(e) = \frac{1}{2}\left[1 - \sqrt{\frac{\gamma_0}{1+\gamma_0}}\right], \quad \text{with fading}$$

- Where γ_0 is the SNR

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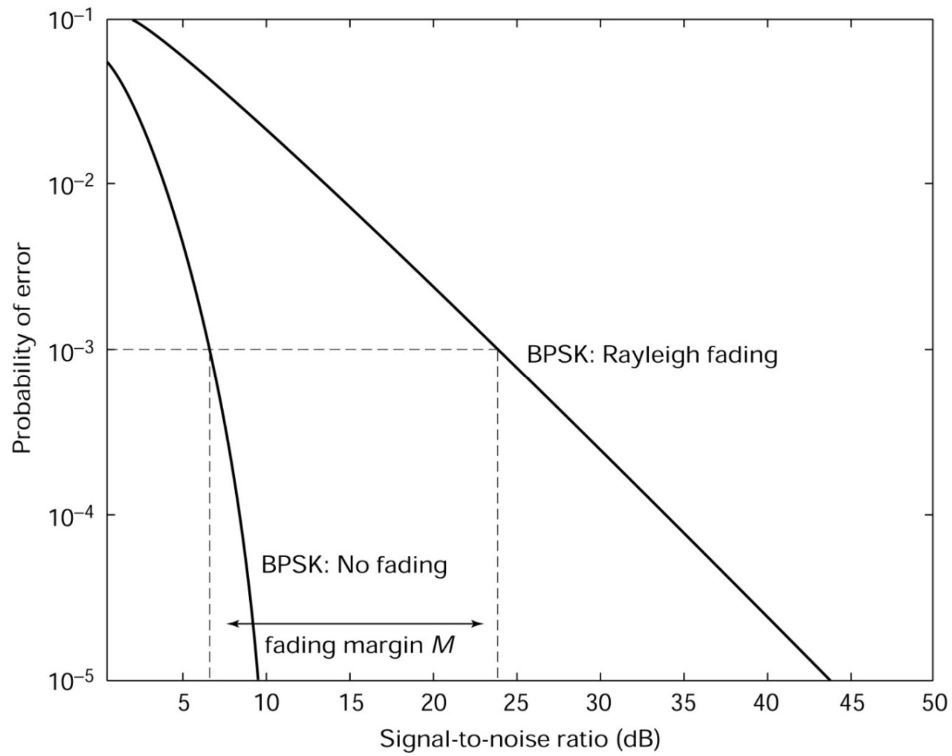
Effects of fading (II)

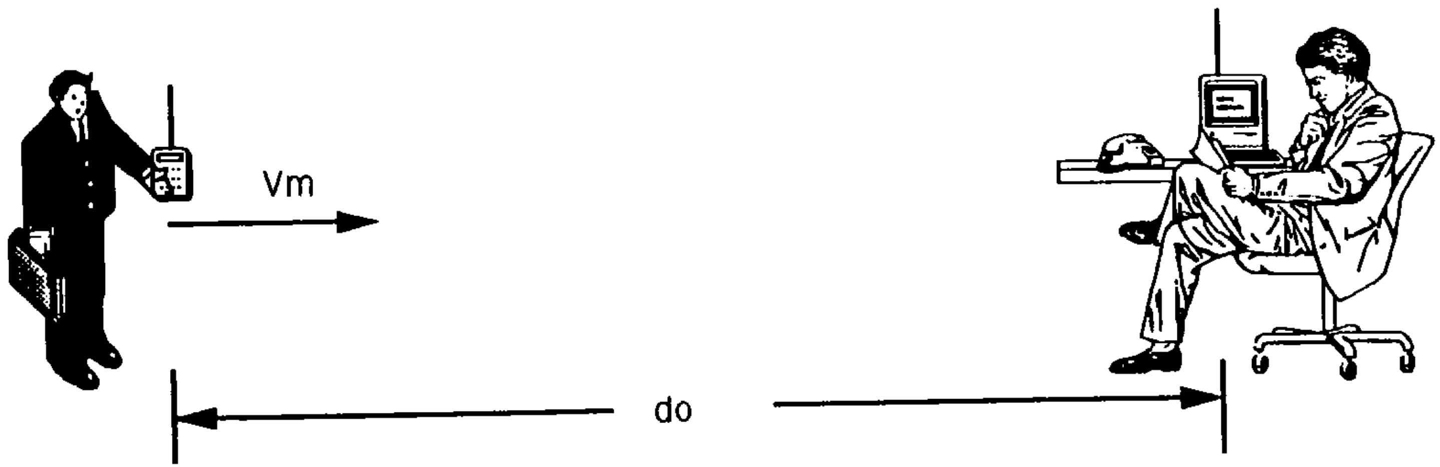
- BER for BPSK-modulation without fading and with Rayleigh-fading
  - Fade-margin *M* for BER=10^{-3} is 17 dB



Other signal degrading effects

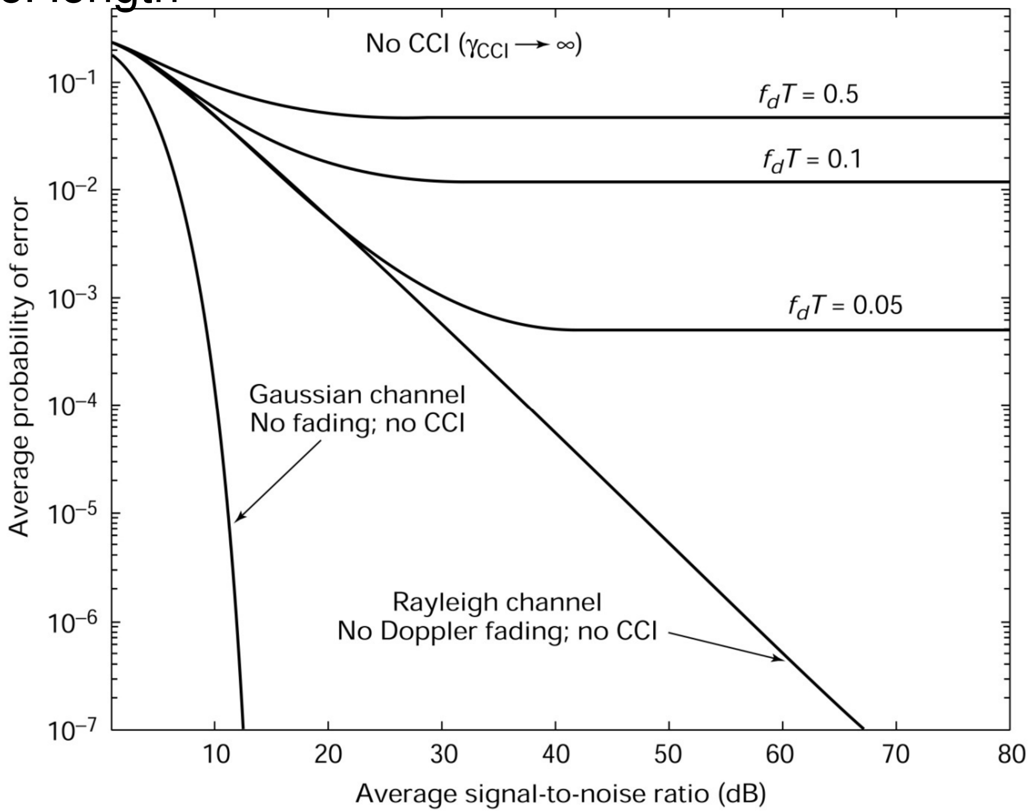
- Random frequency modulation (FM) because of Doppler (chap. 2)
- Co-channel interference (chap. 4)
  - Both these effects creates a «floor» for the BER. BER will not go below a certain value even with increased SNR

- Intersymbol interference (ISI) because of frequency selective fading



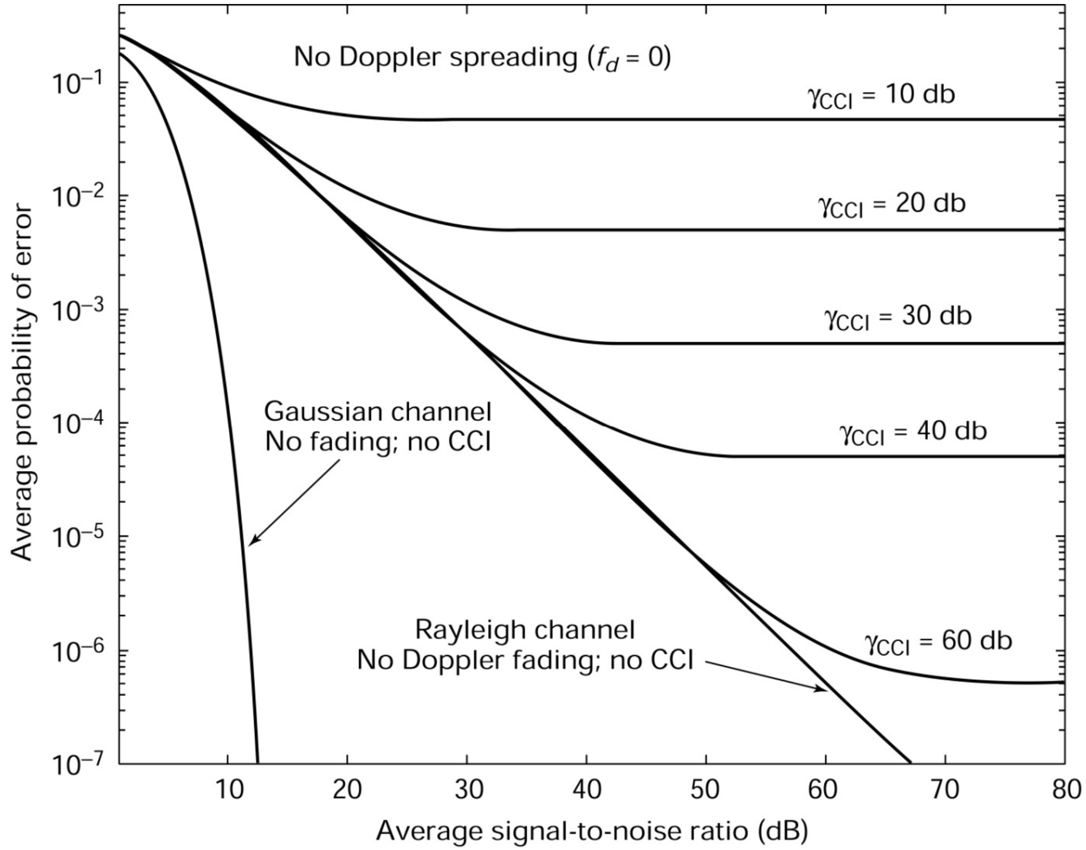
Signal degradation from Doppler

- BER for different values of the product $f_d T$, where f_d is maksimum Doppler-skift and T is the symbol length



Signal degradation from co-channel interference

- BER for different values of the signal-to-interference ratio γ_{CCI}.



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Diversity (I)

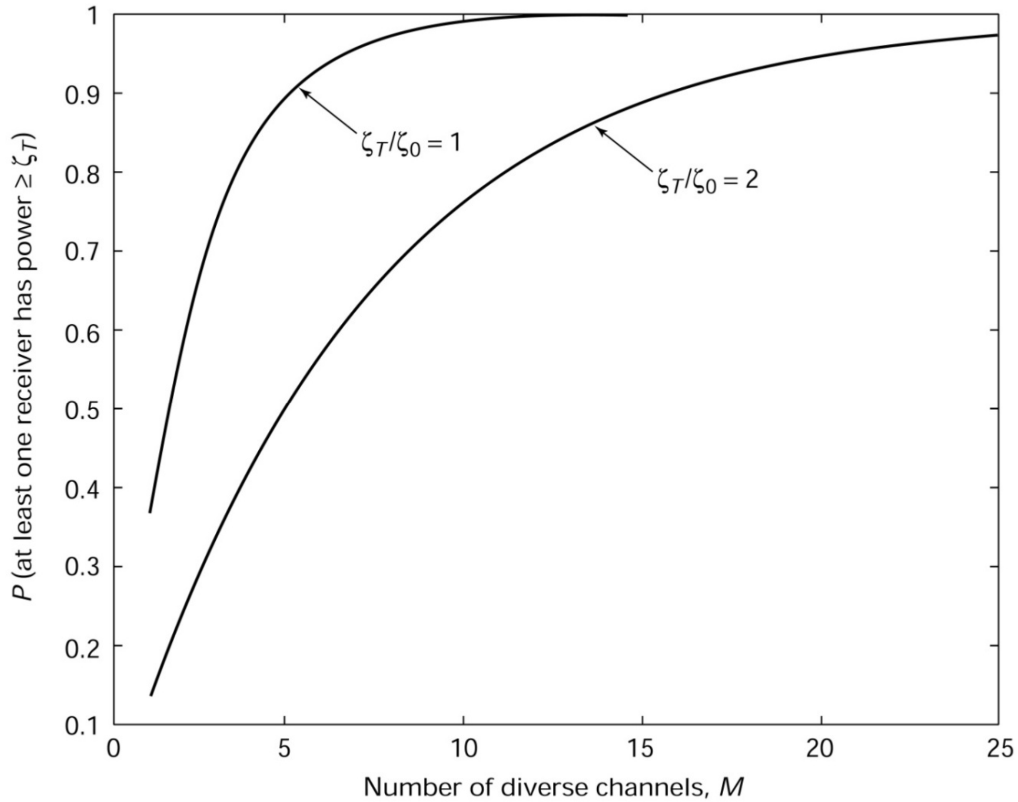
- Diversity means the *combination of independent copies of the received signal*, for example, by using multiple receiver antenna
- The main idea is *the probability that several independent versions of the signal has very low signal level at the same time is small*.
- For example, the probability that M independent Rayleigh distributed signals at the same time is below a threshold value ζ_T is:

$$P_M(\zeta_T) = \left[1 - \exp\left(-\frac{\zeta_T}{\zeta_0}\right)\right]^M$$

- where ζ_0 is the average power

Diversity (II)

- The probability that at least one of M independent Rayleigh fading channels has power above ζ_T:



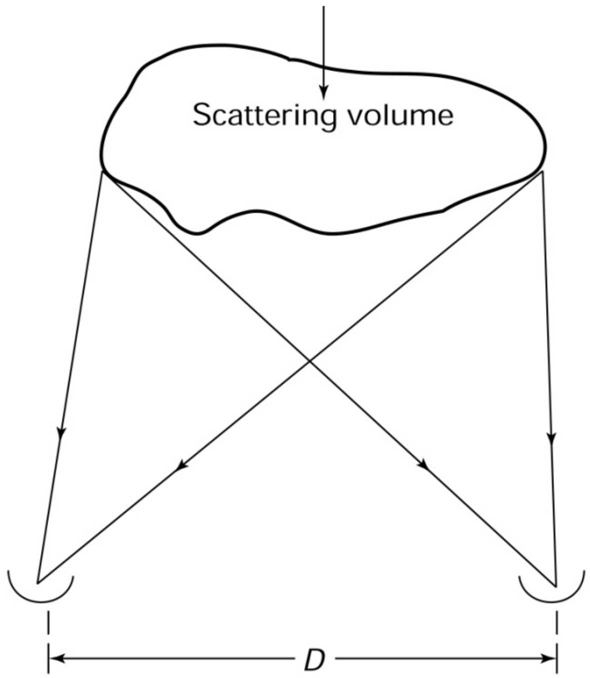
Types of diversity

- *Space diversity –*
  - Antenna separated in distance
- *Angular diversity –*
  - Antennas with different pointing directions
- *Frequency diversity –*
  - The same signal is transmitted at different frequencies
- *Polarization diversity-*
  - Antennas with different polarization (field orientation)
- *Time diversity –*
  - The same signal is repeated at different times
- *Multi-path diversity –*
  - Signals with different propagation paths are combined

Space diversity

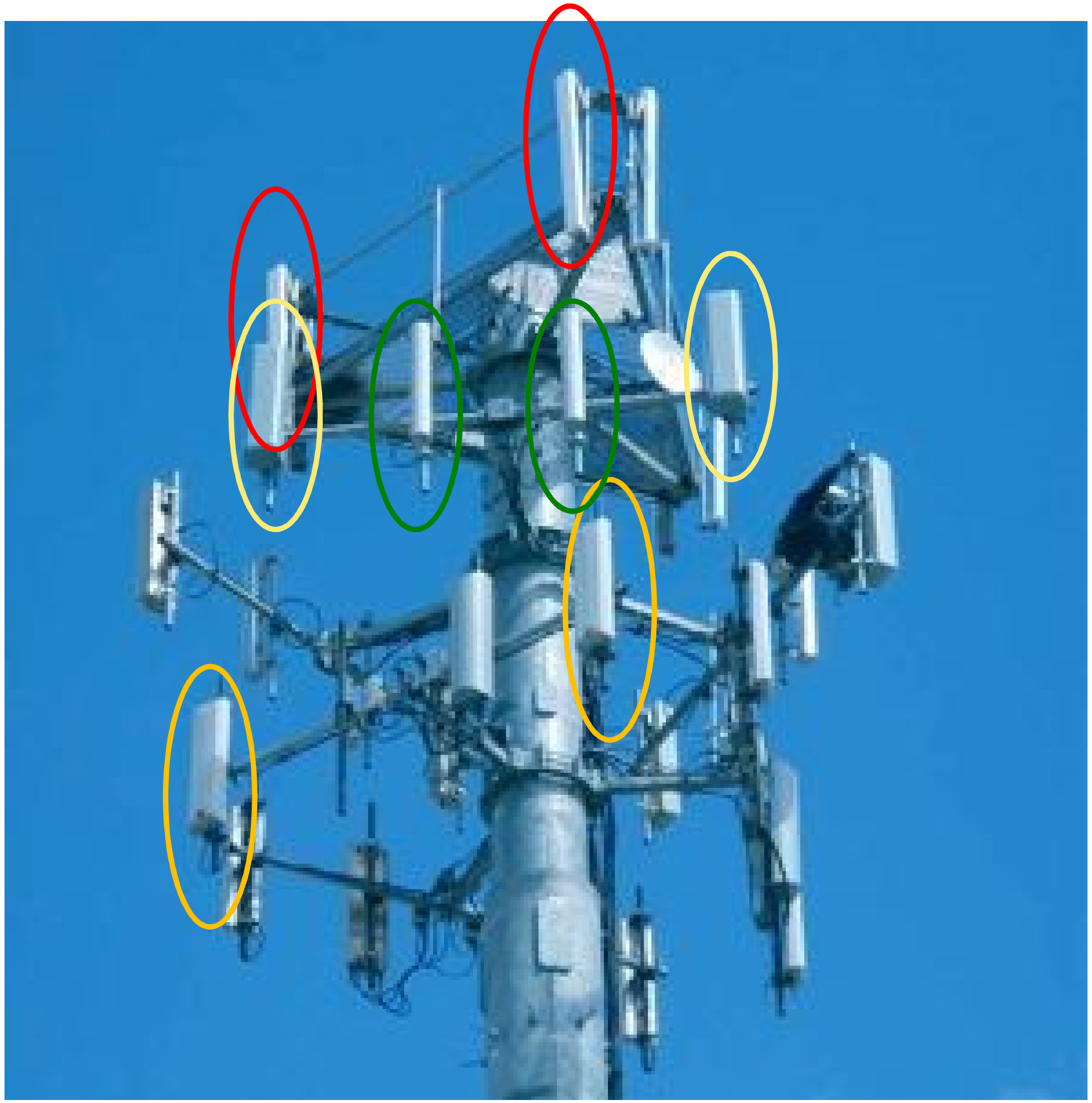
- Two or more antennas in different positions have *uncorrelated fading patterns* if separation is large enough
- Required separation depends on the *angle separation* of the signal components

- Extremes are:
  - If multi-path components arriving with equal probability from all directions necessary distance between two antennas is λ / 2
  - If all signal components arrive from the same direction space diversity will have no effect, no separation is large enough



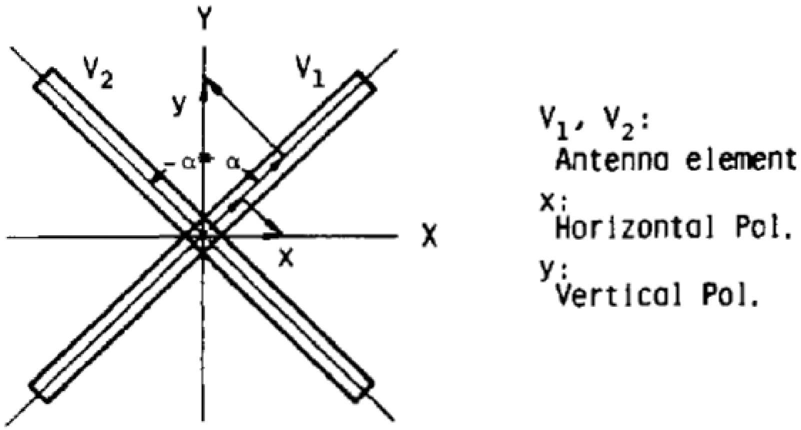
(*a*)

Space diversity at the base station



Polarization diversity

- Signal at different polarization has uncorrelated fading
  - For example vertical polarization & horizontal polarization
- Exploits that the channel depolarizes the signal and that the signal received on different polarizations are fading uncorrelated
- Disadvantage of this method is that a maximum of 2 uncorrelated polarization can exist (diversity order 2)



(a)

S. Kozono et al., Base Station Polarization Diversity Reception for Mobile Radio. *IEEE Trans. on Veh. Tech.*, vol. VT-33, no. 4, Nov., 1984

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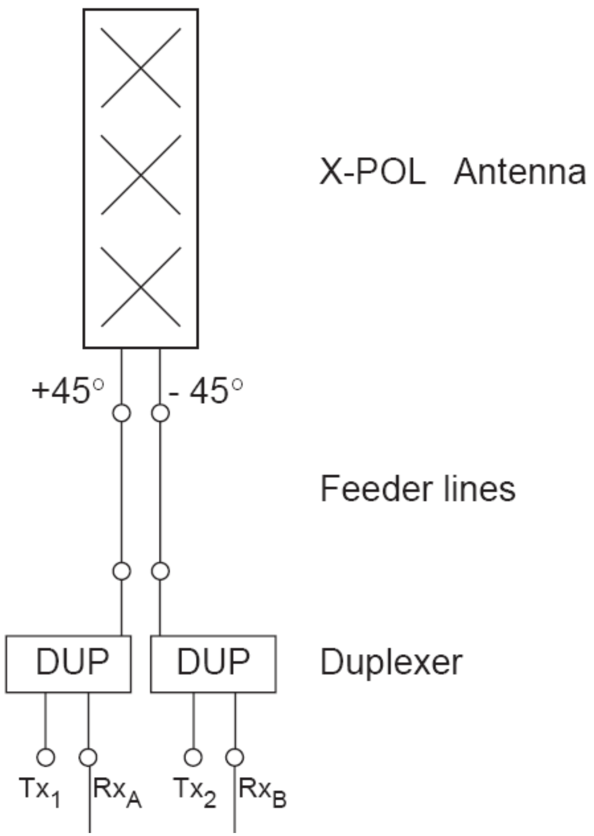
Polarization diversity at the base station



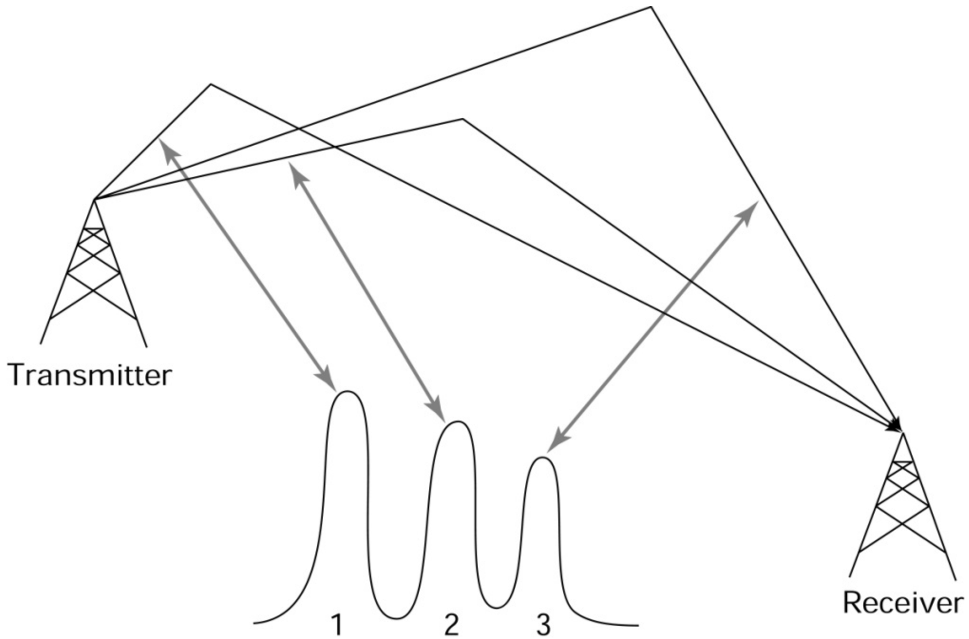
Cross polar antenna used increasingly to save space

+/- 45° is normal

Source: Kathrein

Multipath diversity

- If multi-path components have a large enough separation that the can be distinguished from each other, they can be combined in the receiver
- This is used in RAKE receivers, which are widely used in CDMA systems (Chapter 6 – course book)



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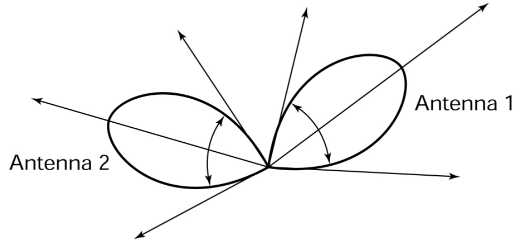
Other diversity concepts



- **Angular diversity:**
  - The receiving antennas have different pointing direction.
  - Signal components arriving from different directions is normally uncorrelated
  - Angular diversity requires no physical distance between the antennas, and can therefore easier implemented on a mobile station
- **Frequency diversity:**
  - The same signal is sent on different frequencies, with so much distance that the signals are uncorrelated fading (> coherence bandwidth)
  - Only one antenna needed
  - Not bandwidth efficient
  - Not effective over frequency flat channel
- **Time diversity:**
  - The same signal is sent several times, with a difference that exceeds the channel coherence time
  - Only one antenna is required
  - Reduction in efficiency
  - Not effective over slow fading channel
  - Error correcting coding can be viewed as a form of time diversity

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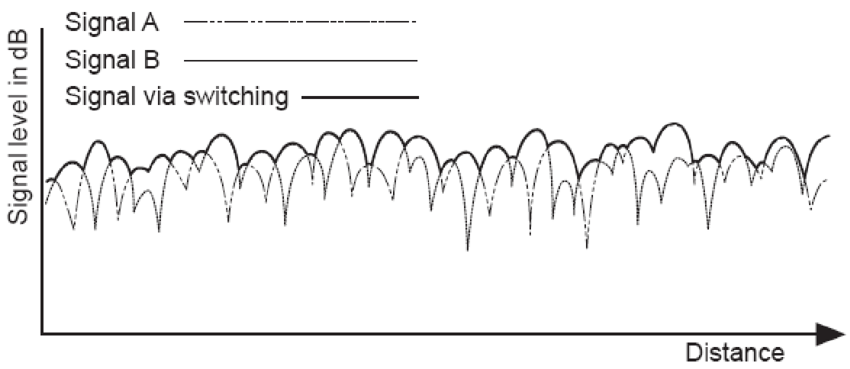
Combining techniques for diversity

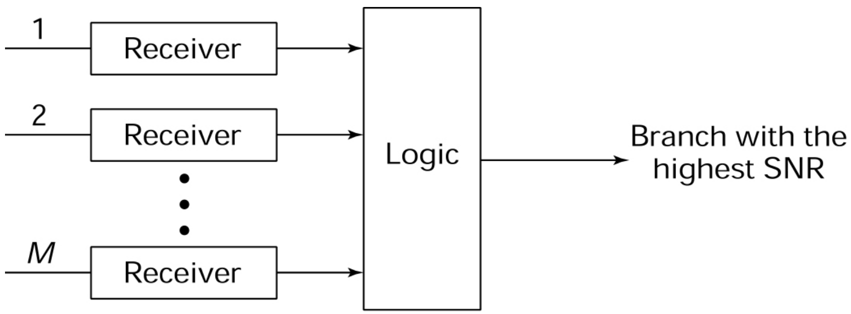
- Selection combining (SC)
  - Selects all times the strongest signal (branch)
- Maximum-ratio combining (MRC)
  - Adds all branches with different weight based on SNR
- Equal-gain combining (EGC)
  - Adds all branches of equal weight

Selection combining (SC)

- Choose the diversity branch with the strongest SNR
- Possible solution to avoid continuous testing of all branches:
  - Use same branch until it goes below a given threshold value, and only then test all the stuff and select the strongest.



Source: William C.Y. Lee, Mobile Communications Design Fundamentals



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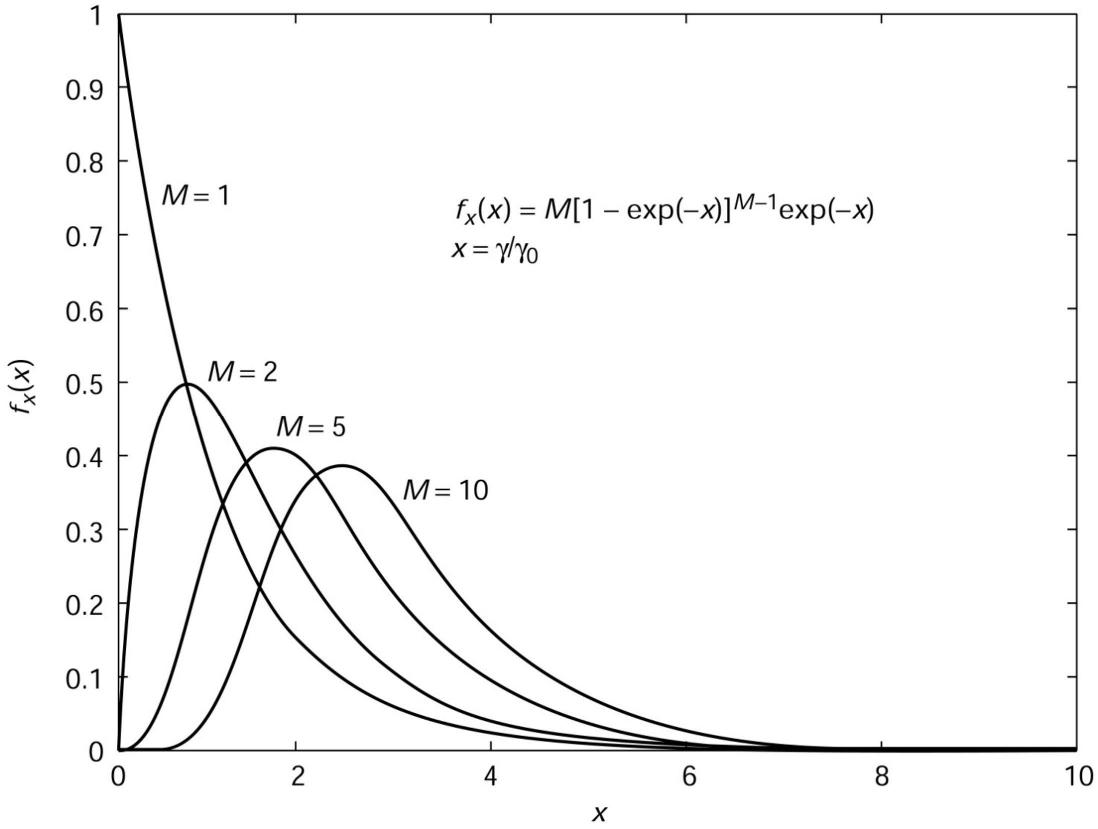
Selection combining (SC)

- Average improvement using selection diversity:

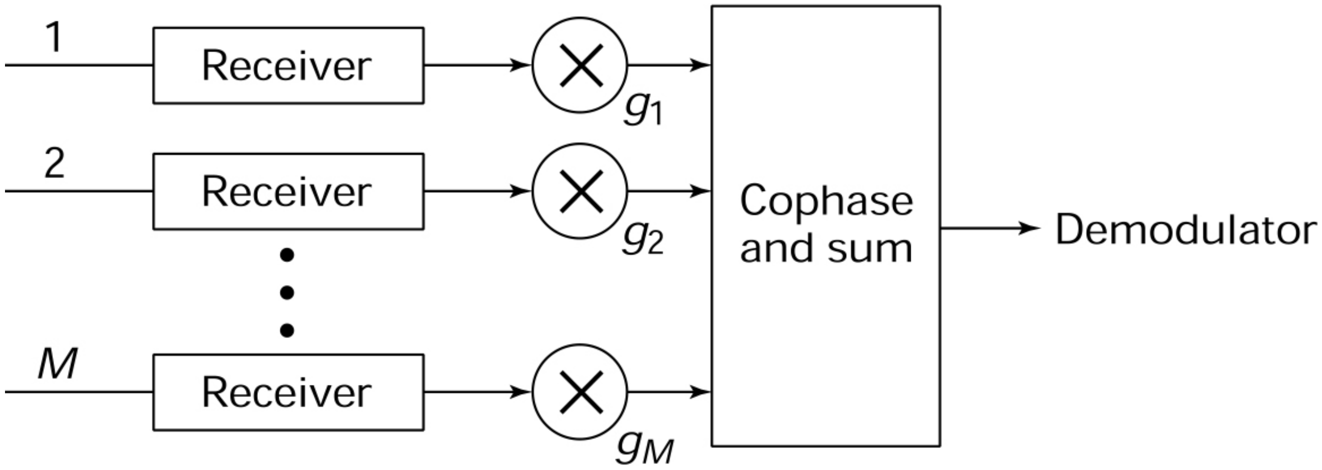
$$\frac{\gamma_{se}}{\gamma_0} = \sum_{n=1}^{M} \frac{1}{n}$$

- Probability density function for γ_{se}/γ_0.



Maximum-ratio combining (MRC)

- Scales all the branches by a factor gn that is proportional with SNR of each branch
- This is an optimum way to combine the signals
  - More complex than selection combining



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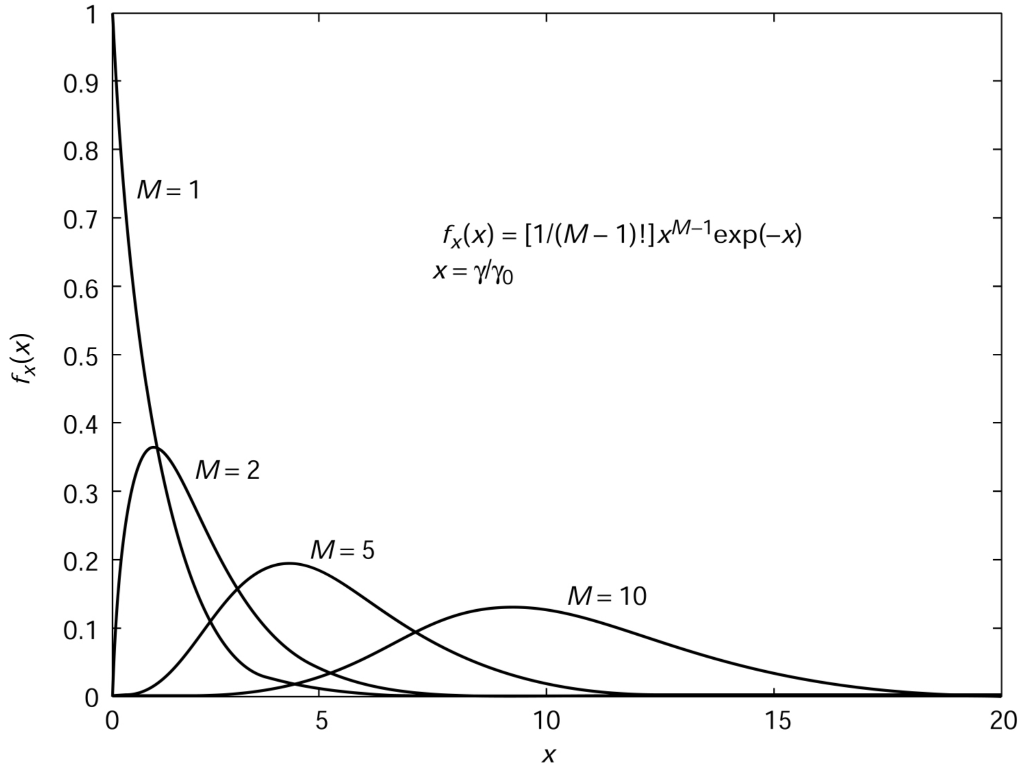
Maximum-ratio combining (MRC)

- Average SNR by using MRC is:

$$\gamma_{MR} = \sum_{n=1}^{M} \gamma_n = M\gamma_0$$

- Probability Density Function for γ_{MR}/γ_0



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Equal gain combining (EGC)

- Scales all branches with the same weight
- Performance is worse than the MRC, but better than SC
- Less complex than MRC
- Performance between SC and MRC,
  - The average SNR by using EGC is:

$$\gamma_{EC} = \gamma_0 \left[1 + \frac{\pi}{4} (M - 1) \right]$$

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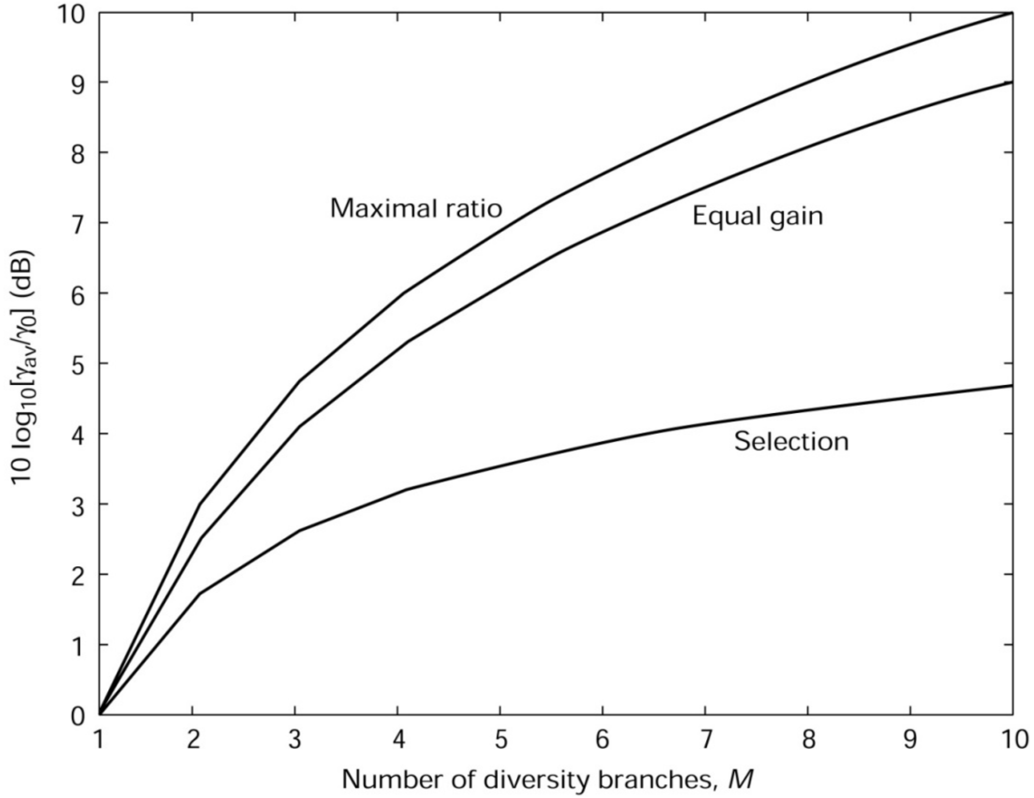
Comparing diversity methods:

- All results are for an assumption of uncorrelated branches, with a correlation equal to ρ, performance is reduced approx. a factor √(1-ρ)2



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Performance improvement – BER with diversity

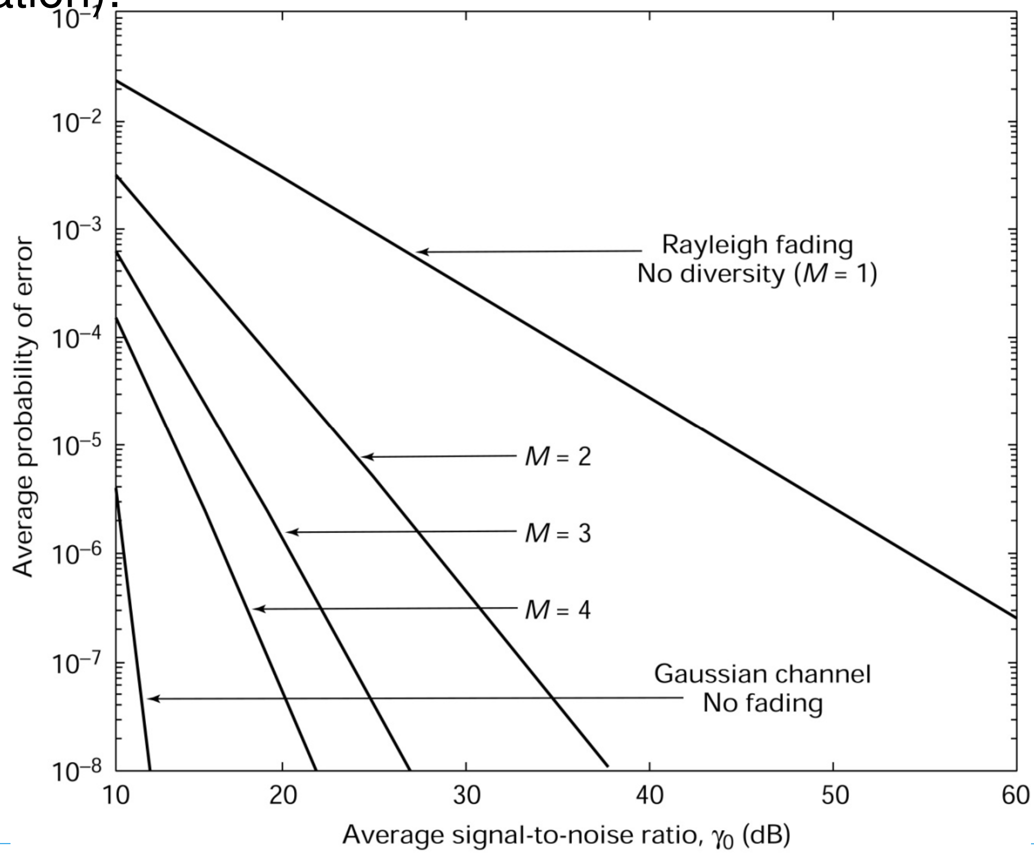
- Average BER for a diversity method can be found using the following expression:

$$p_{av}(e) = \int_0^{\infty} p(e) f(\gamma) d\gamma$$

- Where p(e) is the bit error probability as a function of SNR, γ, and f(γ) is the probability density distribution of the SNR.
- This gives the BER as a function of average SNR, γ_0.

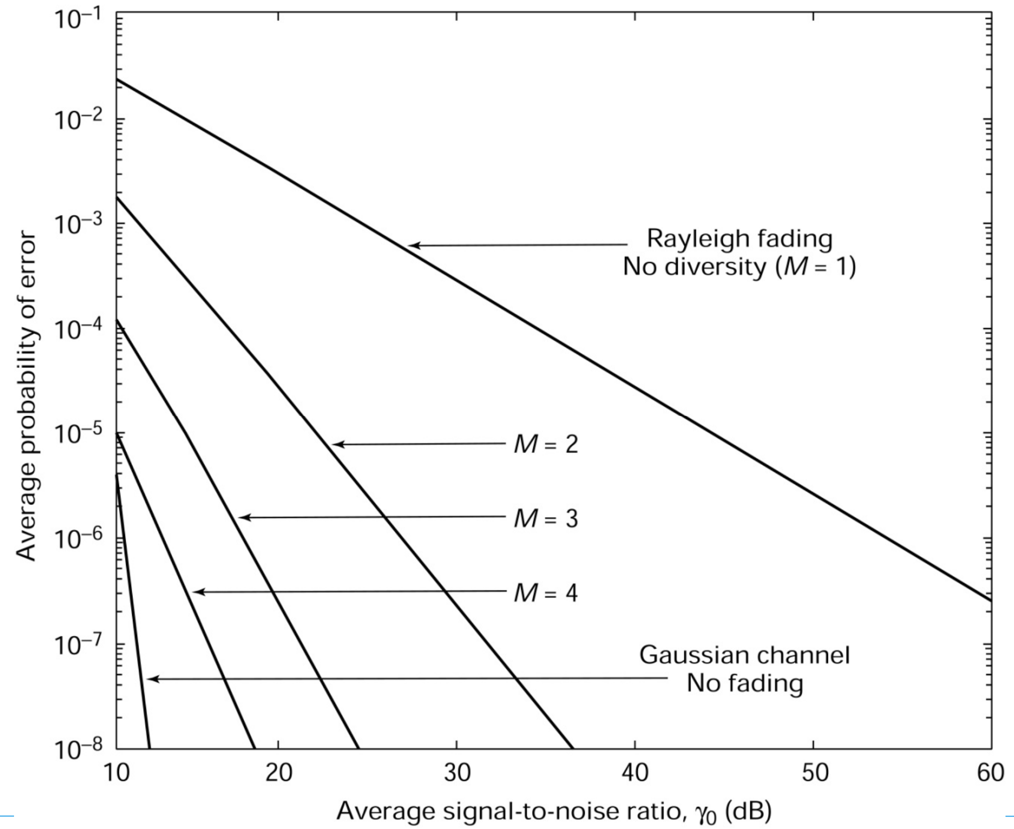
Performance improvement - SC

- Average BER for selection combining for different number of diversity channels (BPSK modulation):



Performance improvement – MRC (1)

- Average BER for maximum-ratio combining for different number of diversity channels (BPSK modulation):



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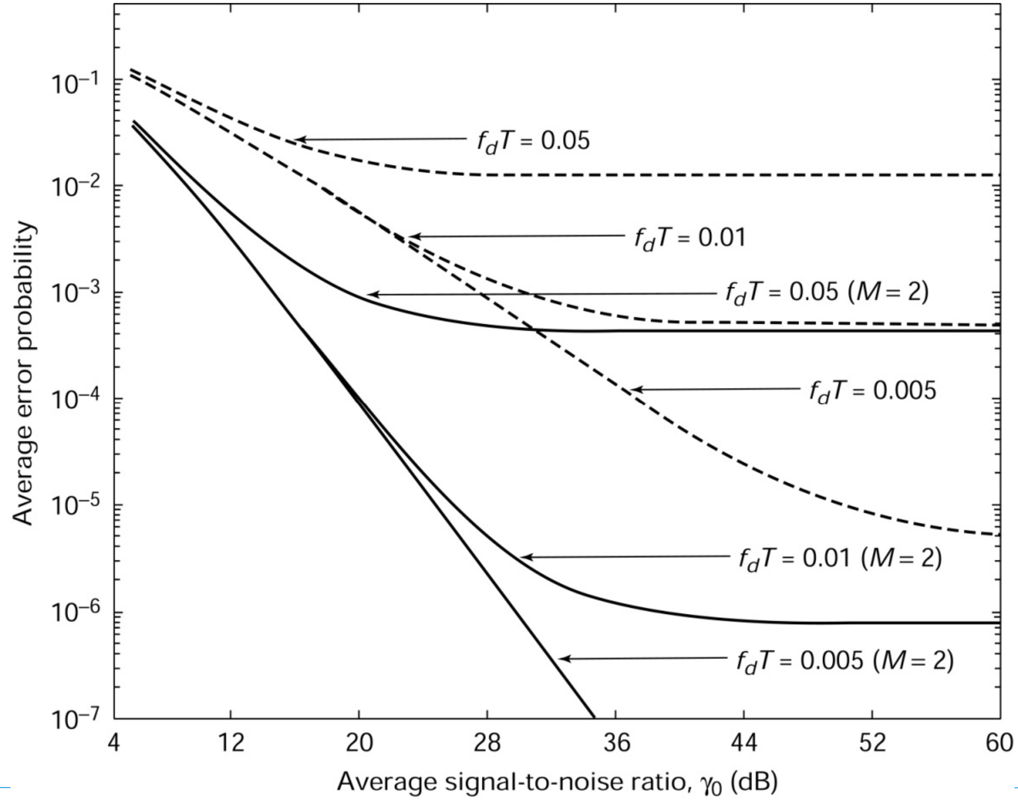
Performance improvement – MRC (2)

- Average BER without diversity and with two-branch maximum ratio-combining
- Diversity lowers the "floor“ for the bit error rate -



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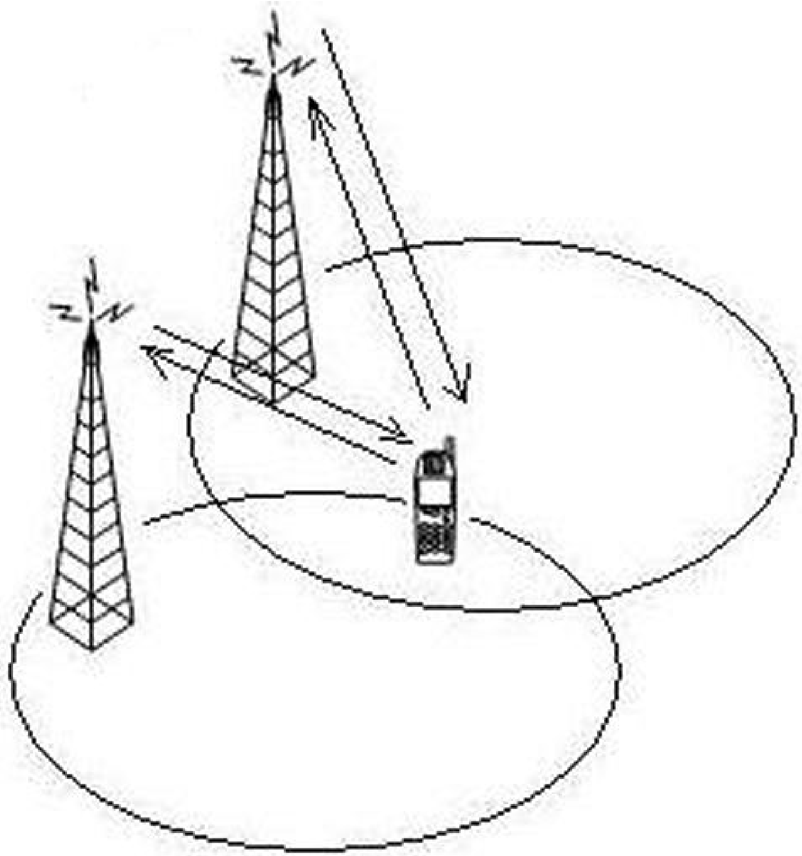
Macro diversity

- The techniques discussed so far fights fast (short term) fading
- To combat slow (long term) fading required separation between recipients who are high in relation to terrain and building formations affects the signal distribution
- This is called macro-diversity, or the base station diversity and is usually based on communication with two or more base stations
- Hand-over of the mobile systems can be seen as a form of macro diversity



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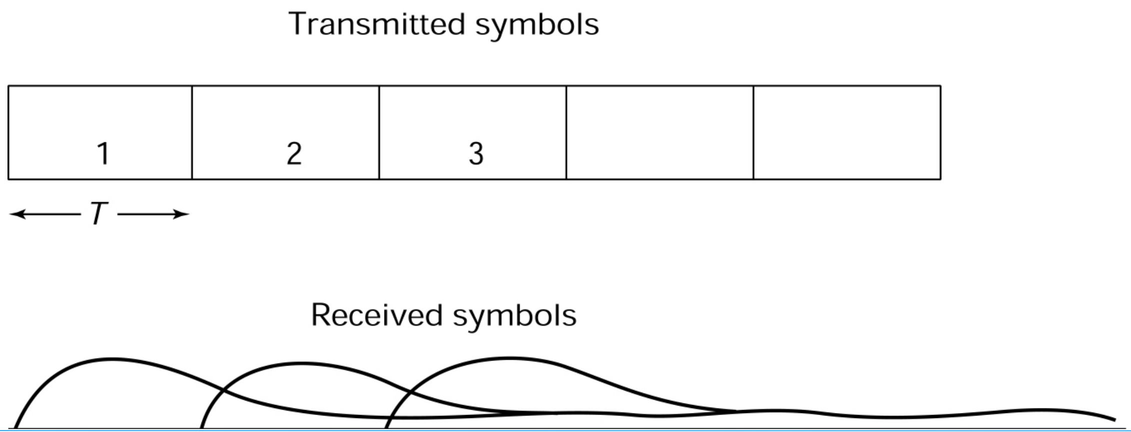
Channel equalization

- When the time dispersion is significant compared to the symbol length it leads to *Inter-Symbol Interference* (ISI)
- In the frequency domain, this corresponds to the coherence bandwidth being smaller than the information bandwidth, which leads to frequency selective fading
- ISI is a particular problem at high rates, when the symbol times are short
- ISI can be mitigated by using channel equalization, which means to filter the signal so that it counteracts the frequency-selective fading and ISI



Equalizer requirements (I)

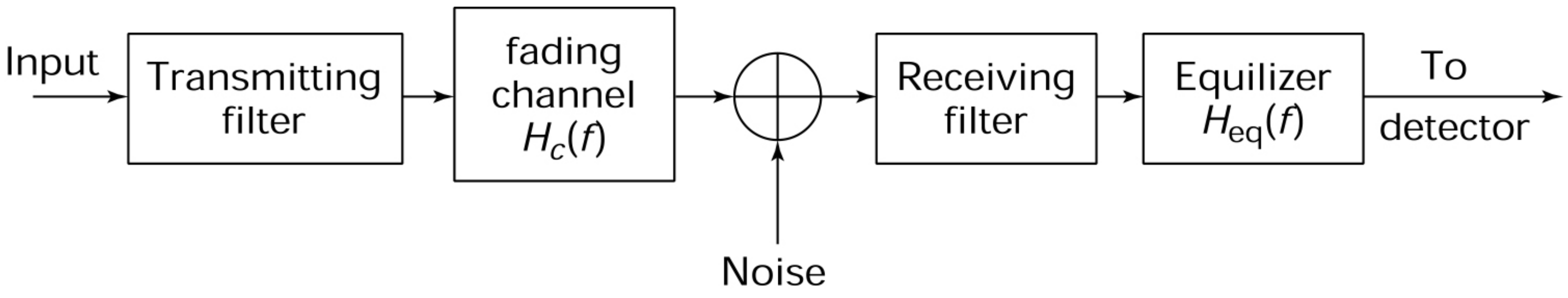
- The transfer function of the channel is: $H_c(f) = A(f)\exp[\theta(f)]$
  - Where $A(f)$ is the amplitude and $\theta(f)$ is the phase response
- The envelope delay is: $\tau(f) = -\frac{1}{2\pi}\frac{d\theta(f)}{df}$
- The criterion for a distortion free channel is: $A(f) = A_0, \quad \tau(f) = \tau_0$
  - Constant amplitude and linear phase (within the information bandwidth)
  - If this is not fulfilled, the signal will be distorted and experience ISI

Equalizer requirements (II)

- The equalizer is a filter with a response $H_{eq}(f)$ such that the resulting response of the channel and equalizer fulfils the requirement of a distortion free channel

$$H_{eq}(f)H_c^*(-f)=1$$

- The channel is time-variant and the filter must be adaptive



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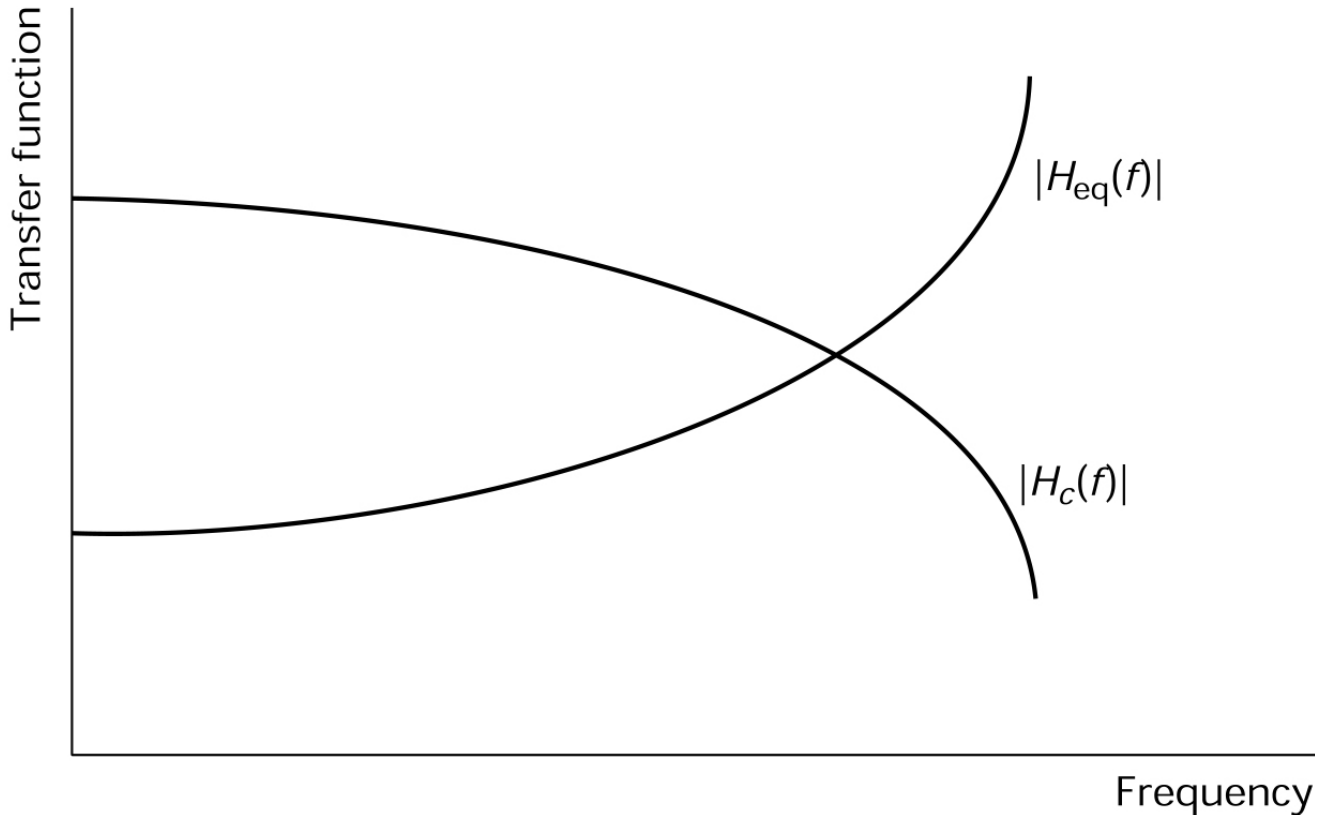
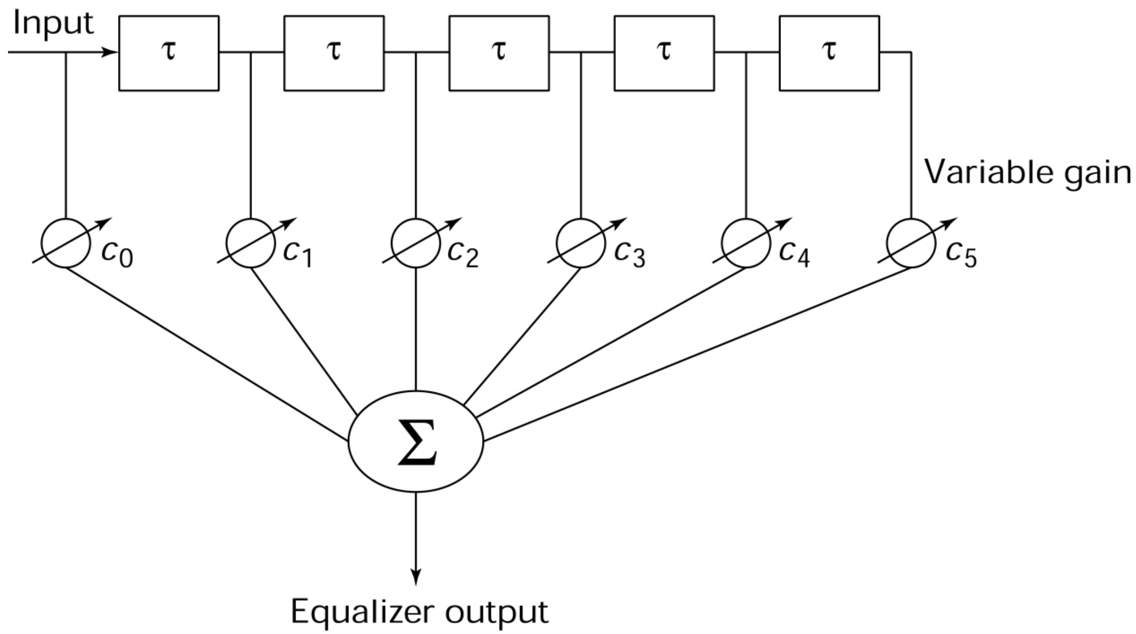
Channel response and equalizer response

- The equalizer response has to compensate for the channel response to make the sum equal, i.e. the channel response is «equalized»



Linear Transversal Equalizer (LTE)

- An LTE structure is shown below
- The required length of the filter depends on the variation in channel delay (the length of the channel's impulse response)



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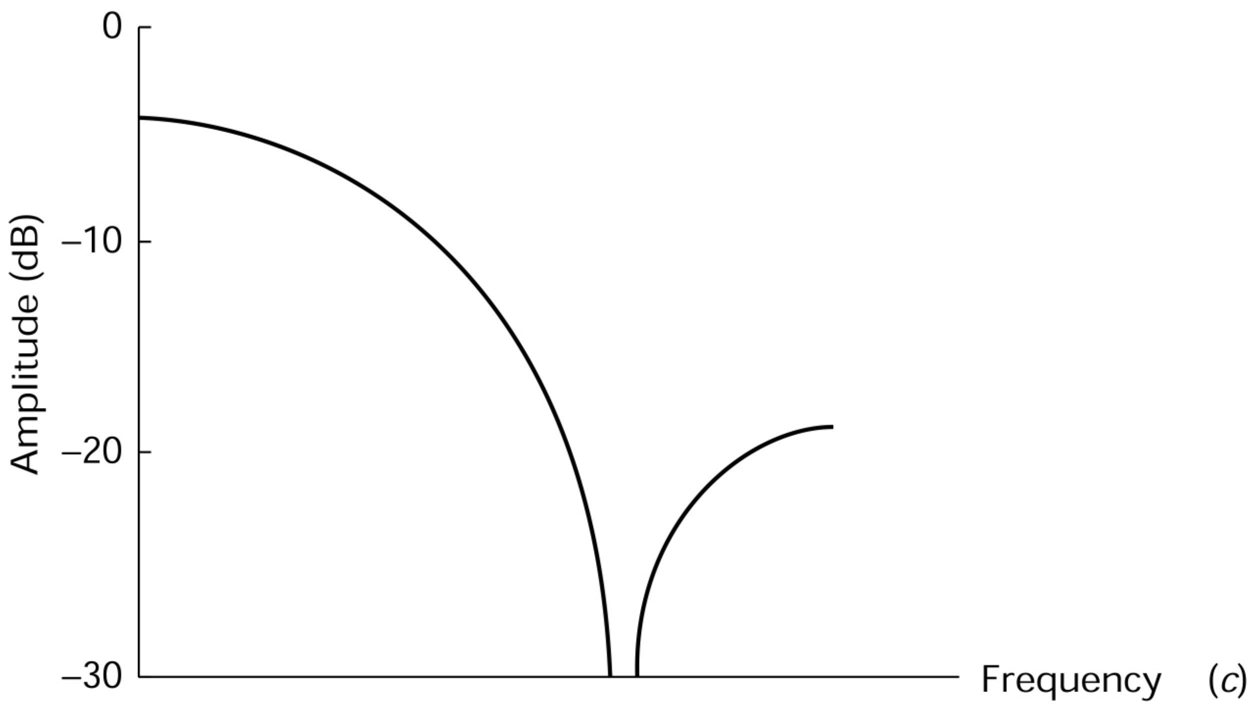
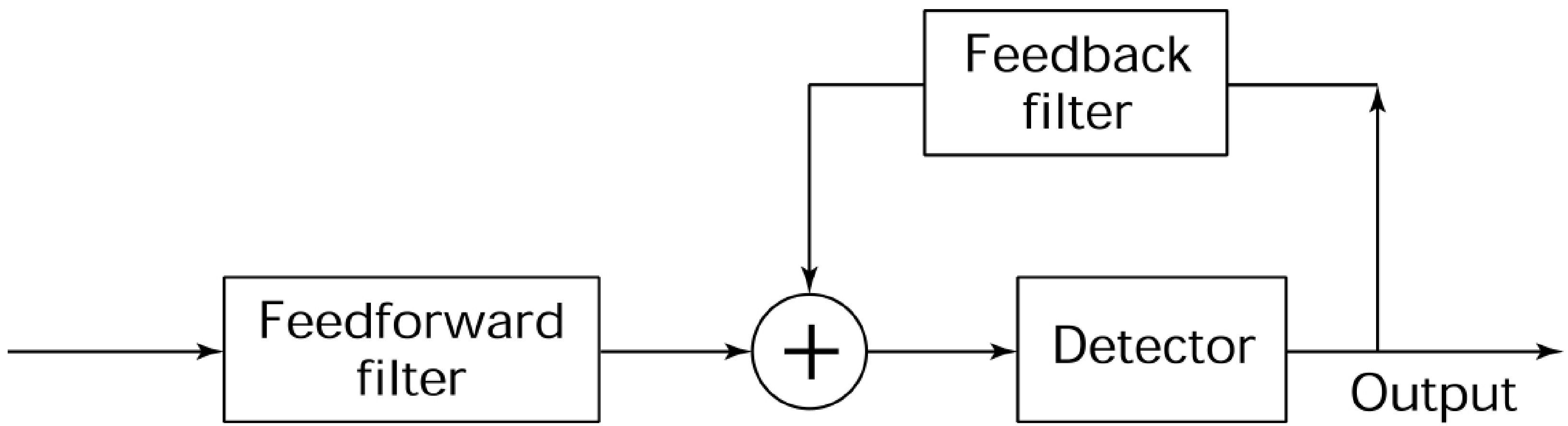
Non linear equalizers

- In some cases, non-linear equalizers are suitable, especially when the channel experiences deep nulls



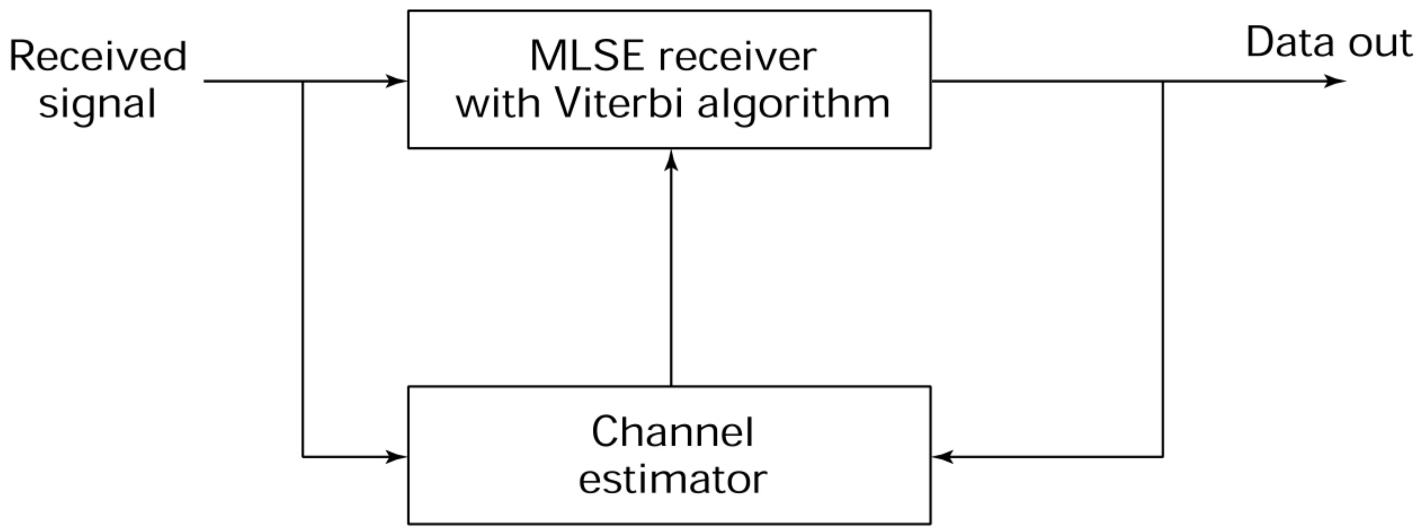
Decision feedback equalizer (DFE)

- The feedforward filter is usually a fractionally spaced equalizer
- The feedback filter is usually a symbol spaced equalizer
- The input of the feedback filter consists of previously detected symbols and the feedback filter subtracts the amount ISI introduced by these symbols



Maximum Likelihood Sequence Estimator (MLSE)

- The channel impulse response is calculated
- A Viterbi algorithm is used to estimate the most likely symbol sequence
- MLSE is an optimum method for removing ISI
  - But the complexity increase exponentially with the length of the channel response



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  - Literature:
    1. David Gesbert and Jabran Akhtar: «Breaking the Barriers of Shannon's Capacity: An Overview of MIMO Wireless Systems». *Telektronikk,* 98(1), p53-54, 2002.

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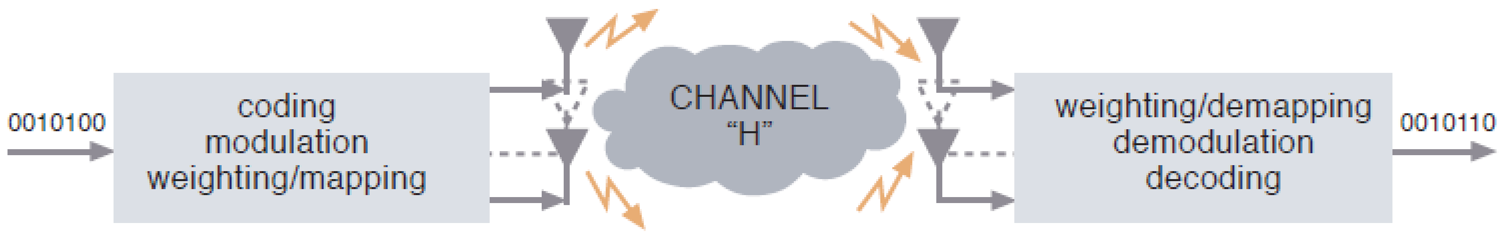
What is MIMO?

- MIMO: *Multiple input – multiple output*
- Given an arbitrary wireless communication system:
  - *”A link for which the transmitting end as well as the receiving end is equipped with multiple antenna elements”*



- The signals on the transmit antennas and receive antennas are ”combined” to improve the quality of the communication (ber and/or bps)
- MIMO systems use space-time processing techniques
  - Time dimension is completed with the spatial dimension

Different gains of multiple antenna systems

- **”Smart antenna” gain**
  - Beamforming to increase the average signal-to-noise (SNR) ratio through focussing energy into desired directions
- **Spatial diversity gain**
  - Receiving on multiple antenna elements reduces fading problems. The diversity order is defined by the number of *decorrelated* spatial branches
- **Spatial multiplexing gain**
  - A *matrix* channel is created, opening up the possibility of transmitting over several spatial modes of the matrix channel increasing the link throughput at no additional frequency, timer or power expenditure

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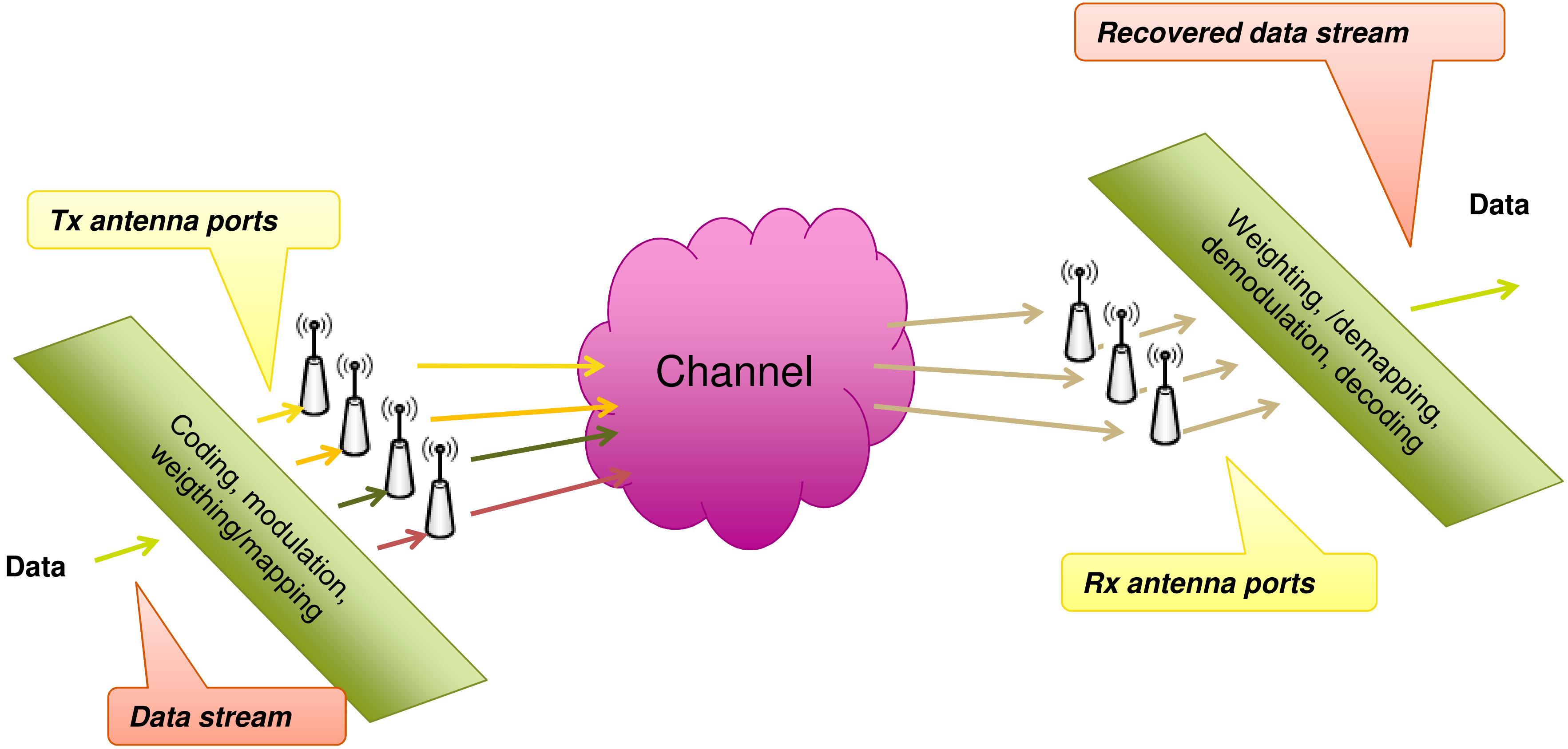
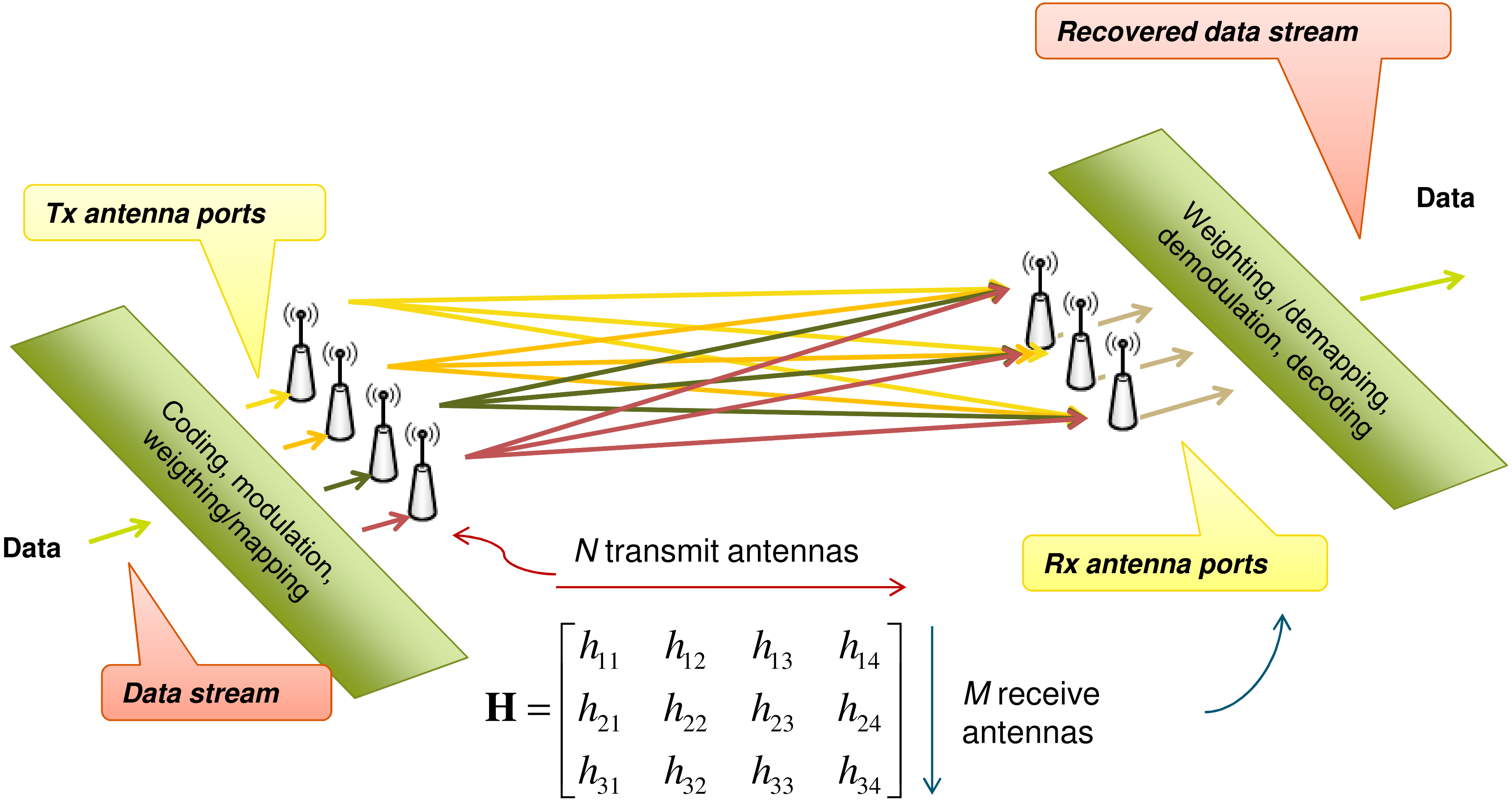
Multiple antenna fundamentals



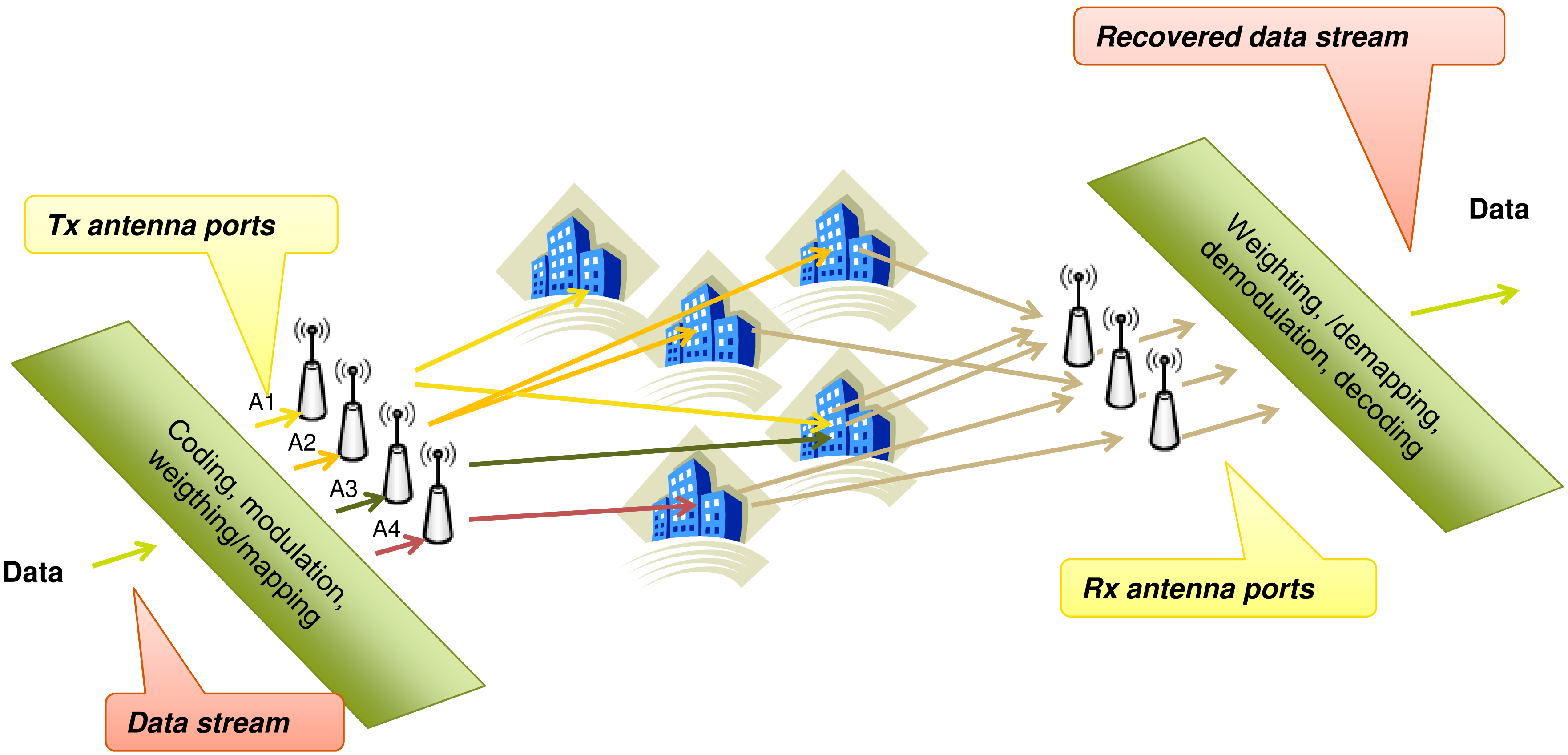
Multiple antenna fundamentals



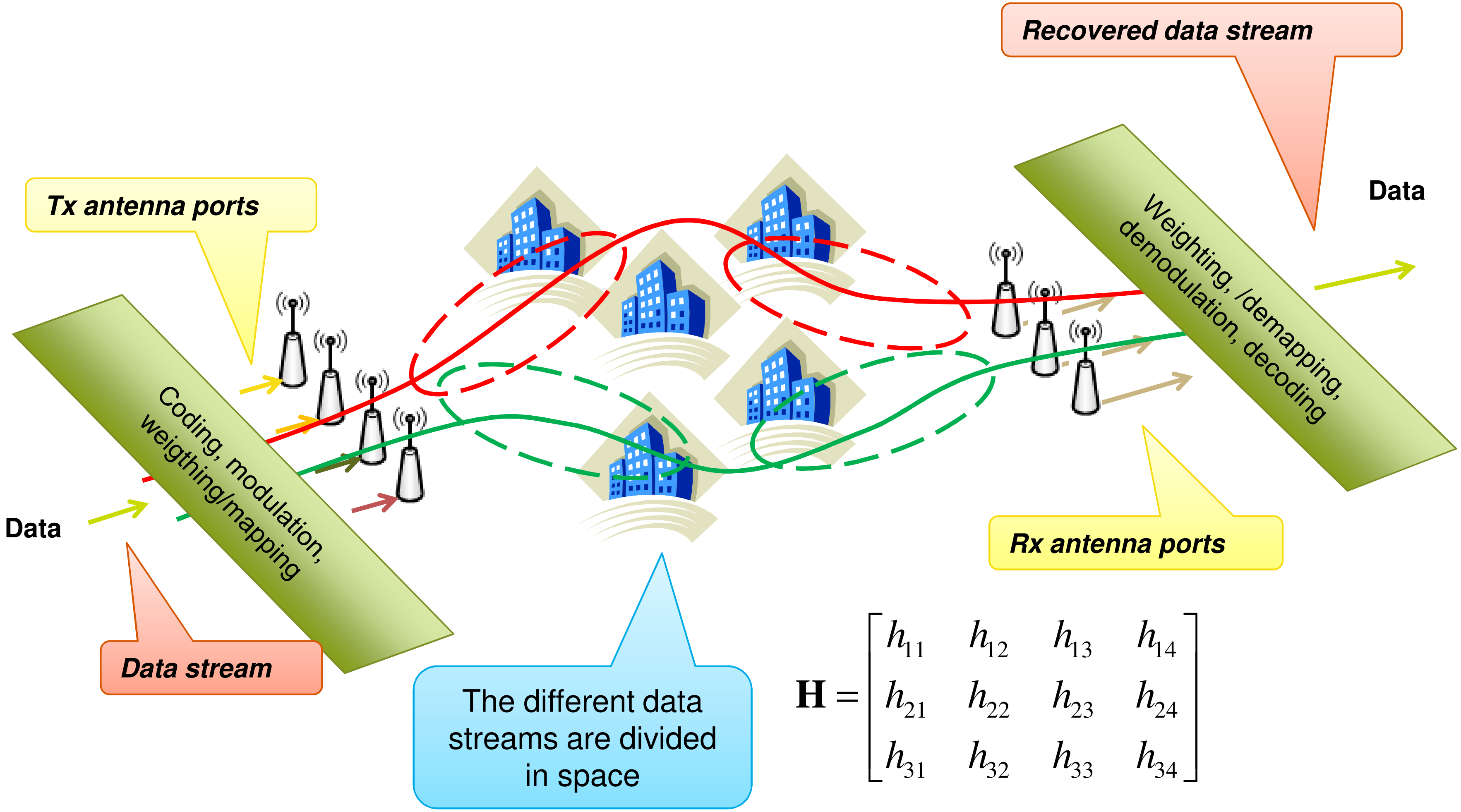
$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \end{bmatrix}$$

Channel matrix

Multiple antenna fundamentals



Multiple antenna fundamentals
Spatial multiplexing



$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \end{bmatrix}$$

rank(**H**) determines how many streams are possible to transmit

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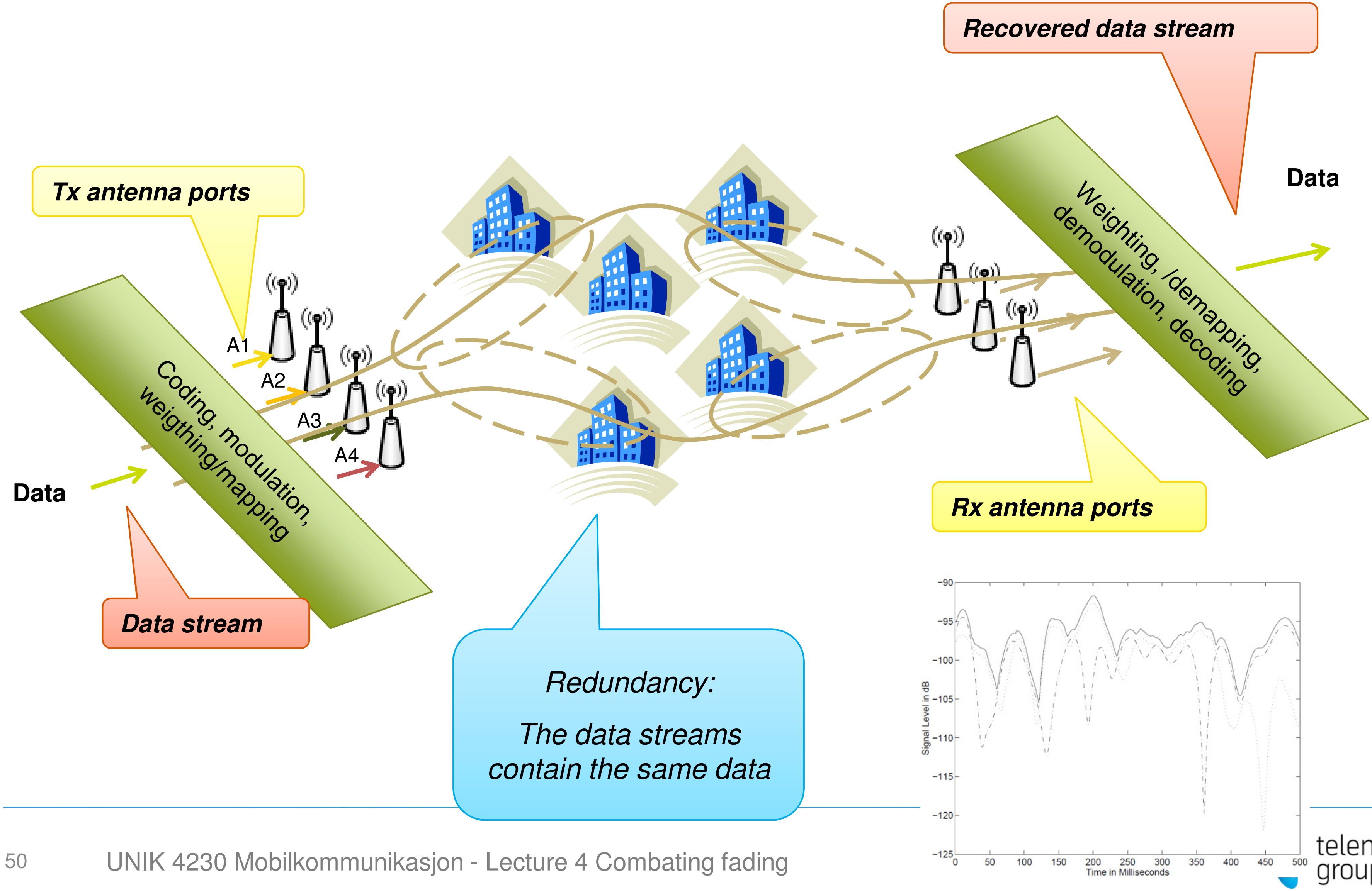
Multiple antenna fundamentals
Transmit diversity



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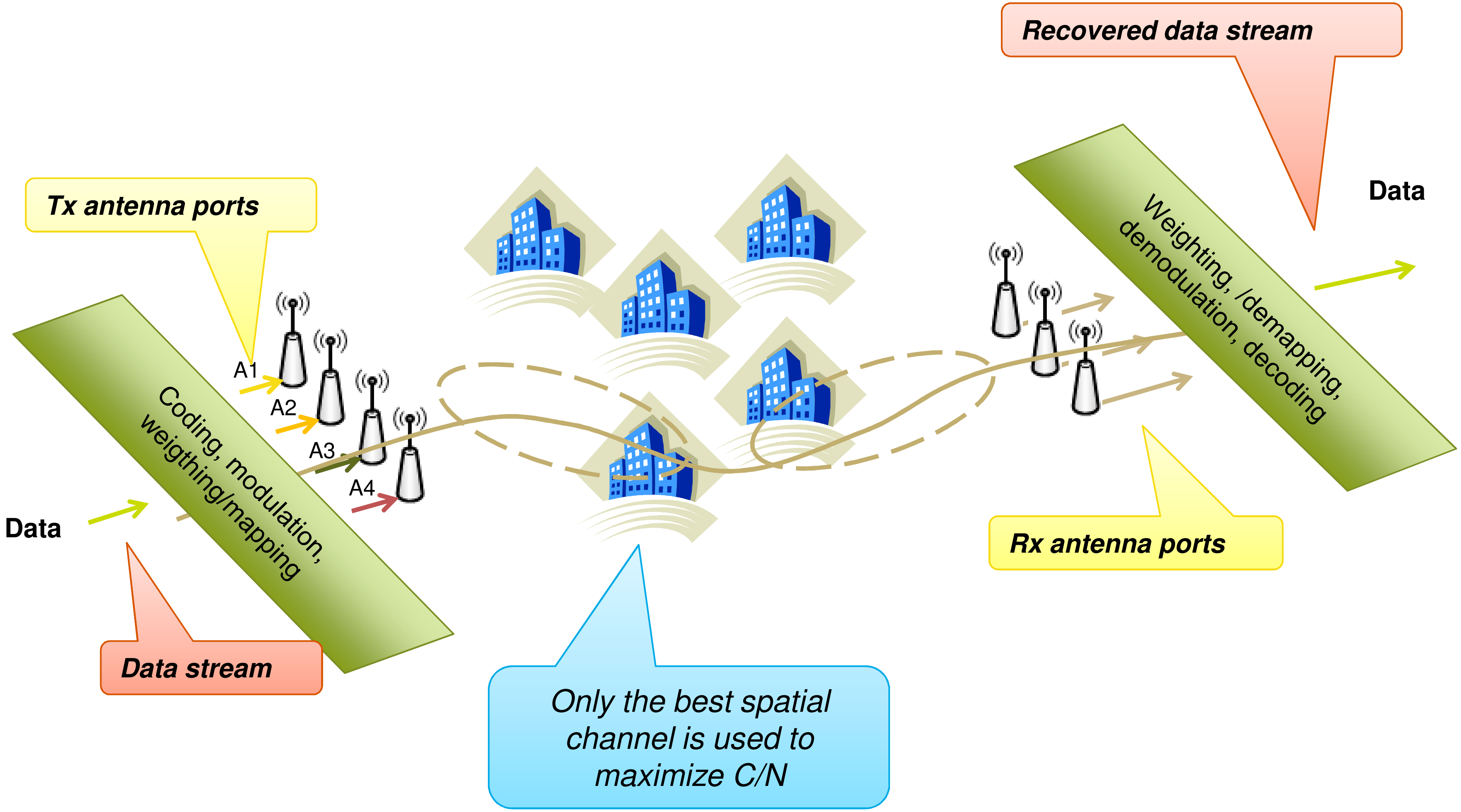
Multiple antenna fundamentals Beamforming



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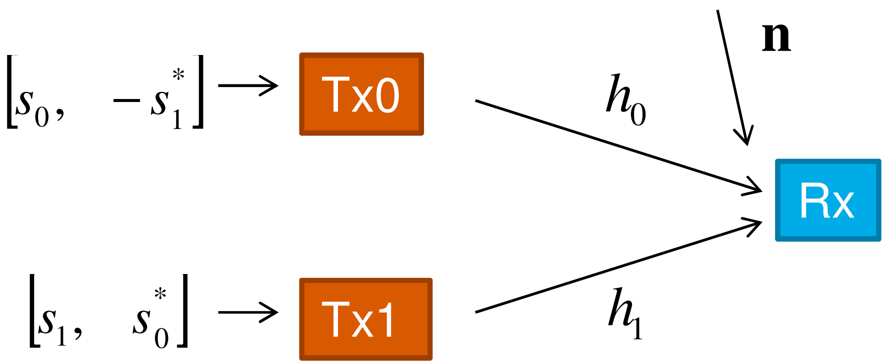
Maximizing diversity with space-time block codes

- Alamouti's scheme:
  - The block of symbols s_0 and s_1 is coded across time and space
  - Normalization factor ensures total energy to be the same the case of one transmitter
- Reception:
  - The receiver collects the observation, $\mathbf{y}$, over two symbol periods

$$\mathbf{C} = \frac{1}{\sqrt{2}}\begin{bmatrix} s_0 & -s_1^* \\ s_1 & s_0^* \end{bmatrix}$$

$$\mathbf{s} = \begin{bmatrix} s_0 & s_1 \end{bmatrix}^T \qquad \mathbf{h} = \begin{bmatrix} h_0 & h_1 \end{bmatrix} \qquad \hat{\mathbf{H}} = \frac{1}{\sqrt{2}}\begin{bmatrix} h_0 & h_1 \\ h_1^* & -h_0^* \end{bmatrix}$$



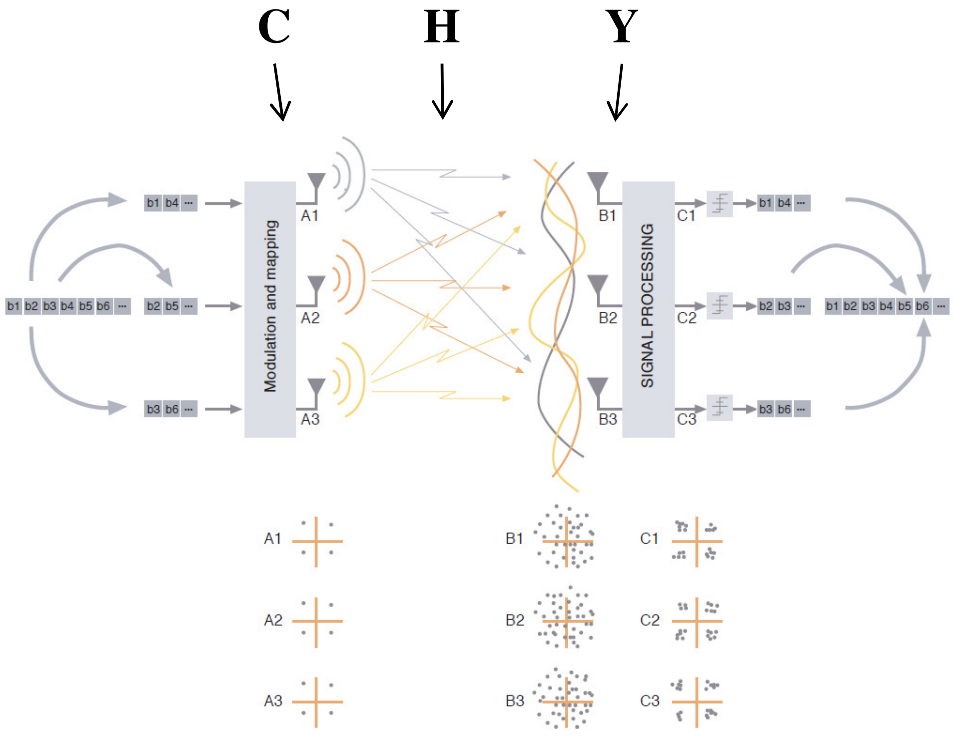
$$\begin{bmatrix} y_0 & y_1 \end{bmatrix} + \mathbf{n} = \mathbf{h}\cdot\mathbf{C} + \mathbf{n}$$

$$\begin{bmatrix} y_0 & y_1^* \end{bmatrix}^T + \mathbf{n} = \hat{\mathbf{H}}\cdot\mathbf{s} + \mathbf{n}$$

Spatial multiplexing

- Extending the Space-Time Block Coding
  - Transmitting independent data over different antennas
  - The receiver must un-mix the channel
  - Limited diversity benefit

$$\mathbf{Y} = \mathbf{HC} + \mathbf{N}$$



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Summary chapter 5

- Signal variations caused by fading increase the BER
- Random FM caused by Doppler and co-channel interference results in a BER «floor»
  - The BER cannot be improved further by increasing SNR
- Diversity means that multiple copies of the signal, which experience independent fading, are combined.
  - This reduces the need for fading margins
- Spatial, frequency, angular, polarization, time and multipath diversity are different types of diversity
- Selection combining, maximum ratio combining and equal gain combining are different methods for combining the diversity signal.
  - MRC is optimum, but also most complex
- Macro-diversity means that the receivers are spaced with large distances, usually different base stations.
  - Macro-diversity fights long-term fading
- Inter-symbol interference (ISI) cased by frequency-selective fading can be mitigated with channel equalizers
- Multiple antennas – MIMO – can be used to exploit multipath transmission

Spare slides

Properties of the Linear Transversal Equalizer

- Different optimizing criteria exists to estimate the values of the filter coefficients c_i.

- Zero-forcing (ZF) tries to force the ISI to zero.
  - This is not always optimum
  - Can give noise amplification in parts of the bandwidth

- Symbol-spaced equalizer:
  - the unit delay between two coefficients is equal to the symbol length T

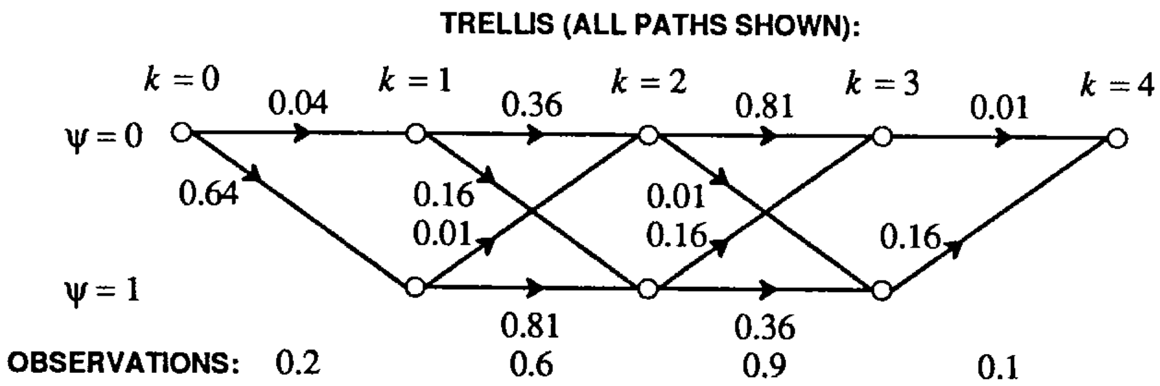
- Fractionally spaced equalizer:
  - The unit delay between two coefficients is less than the symbol length T

How MLSE works

- The Viterbi algorithm finds the sequence s_k through a trellis which minimizes the Euclidean distance between the sequence and an observation:

$$\sum_{k=1}^{K} \left| r_k - s_k \right|^2$$

- Example: $h=1+0.5z\text{-}1$ (fig: [Lee, 1994]) :



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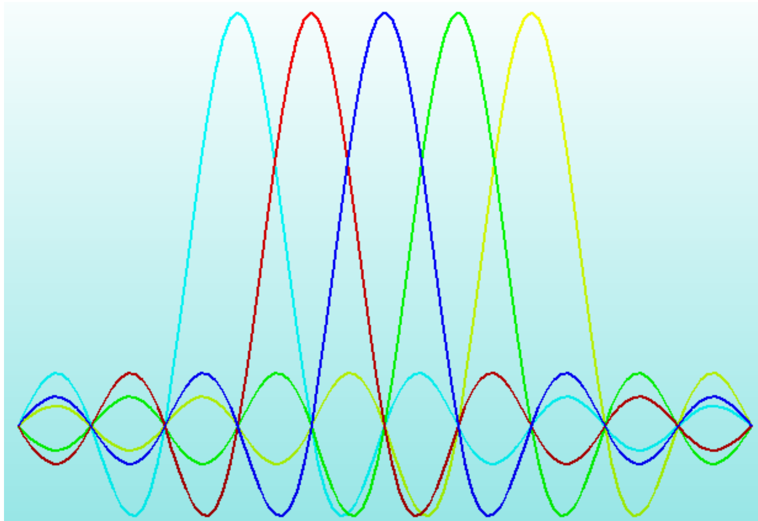
Orthogonal Frequency Division Multiplex (OFDM) (1)

- A fundamental problem in mobile communication is the ISI which occurs when the data rate is high
  - Channel equalizers counteract this, but becomes too complex when they must span many symbol periods
- Another solution is to construct the data stream by using many wave carriers each one having a low data rate
  - This is robust against multipath propagation because each of the carriers have relatively narrow bandwidth, and thereby flat fading
- The highest bandwidth efficiency (bit/s/Hz) is achieved by using overlapping orthogonal carriers



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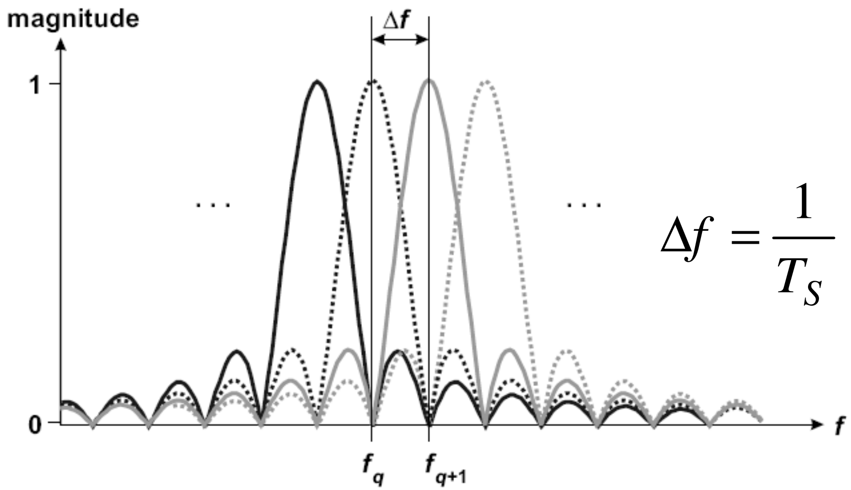
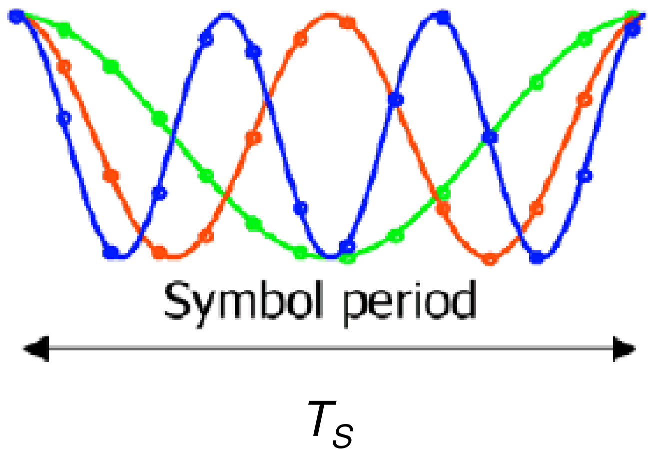
Orthogonal Frequency Division Multiplex (OFDM) (2)

- The individual subcarriers in OFDM can overlap without disturbing each other if the frequencies are chosen to be orthogonal
- This means that during a symbol period, the signal goes through an integer number of cycles.



$$\Delta f = \frac{1}{T_S}$$



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Orthogonal Frequency Division Multiplex (OFDM) (3)

- Because of its good performance in fading channels, OFDM has gained increased popularity
- It is now chosen for most new mobile and wireless systems with high data rates in fading channels

- Examples:
  - Digital terrestrial broadcast (DVB, DAB)
  - New standards for WLAN
    - IEEE 802.11a, g, n (Wi-Fi)
    - IEEE 802.16 (WiMAX)
  - LTE – Long Term Evolution – «4G»